International Mechanical Engineering Conference and Exposition, MEMS Symposia, Anaheim, CA, Nov. 18th, 1998

Convection-based Accelerometer and Tilt Sensor Implemented in Standard CMOS

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***Abstract* - This paper describes a CMOS implementation of novel accelerometers that operate based on heat convection, requiring no solid proof mass. The devices consist of microheaters and thermocouple or thermistor temperature sensors separated by a gap and placed in differential or Wheatstone configurations. Temperature sensors measure the temperature difference between the two sides of the microheater caused by the effect of acceleration on free convection in the surrounding gas. The devices show a small linearity error of <0.5% under tilt conditions from –90 to 90 degrees, and <2% under acceleration from 0 g to 7 g. Sensitivity of the devices is a nearly linear function of heater power (temperature). For operating power between 40 mW and 90 mW, a sensitivity of 40 μV/g to 115 μV/g was measured for thermopile configuration. For operating power of 120 mW to 430 mW, 25 μV/g to 185 μV/g was measured for thermistor configurations. Both types of devices are operable up to frequencies of several hundred hertz.**

I. INTRODUCTION

Miniaturization and integration of accelerometers in standard IC processes has been the topic of extensive research [1]-[3]. In most cases, accelerometer structures involve solid proof mass, which is allowed to move under accelerating conditions. This has many disadvantages, the main one being difficult processing of such components in IC technologies inherently unsuited for such design. More recently, micromachining techniques have brought about many novel miniaturized accelerometer structures, although the fabrication includes many masks and etching steps. It would be very useful to integrate such devices in a standard CMOS technology, where on-chip drive and sense circuitry is available, and start-up costs are lower. For these reasons, many other classes of sensors have been implemented in CMOS by simple post-processing micromachining [4]-[6].

Recently, a novel concept and device structure for acceleration and tilt sensing were developed by Dao *et al* [7], requiring no solid proof mass. The concept of operation of these devices is the effect of acceleration on the natural heat convection from heated resistive wires in a gas surrounding the device. In such a device, the sensor is hermetically packaged to prevent any influence of external airflow or pressure changes on the gas that surrounds the sensor. An implementation of this device by custom fabrication on a silicon substrate was reported recently by Leung *et al* [8]. Although their implementation is a step toward miniaturization and integration, the proposed device required custom fabrication, and only sensitivity to tilting is reported in their paper.

This paper reports on devices implemented in a standard commercial CMOS utilizing micromachined thermopile or thermistor sensors for temperature sensing, and reports measurements under both tilting and accelerating conditions. Our process results in the provision of monolithic integration of drive, detection, and output circuitry with the sensor on a single chip. There is a trade-off with slightly reduced stability because the resistive film available in standard CMOS is polysilicon. However, the capability of fabricating this structure in CMOS technology could have a significant economic advantage as a low-cost accelerometer with integrated electronics. Due to the very miniature scale of these devices, their overall sensitivity is significantly lesser than that of the hand-made devices [7]. As an additional trade-off to miniaturization, integration, and system cost, however, is a significantly improved frequency response (up to hundreds of Hertz vs. several to tens of Hertz). Also, our devices show significantly lowered power requirements.

II. THEORY OF OPERATION

The basic part of the devices is a suspended microheater, previously characterized in [9], which can produce local temperatures of up to 1000 K on the chip. The thermal difference between the heated element and the surrounding gas generates the buoyant force that causes the convective flow of the gas. The convective gas flow (or plume) is the proof mass for this accelerometer. This is shown in Figure 1,

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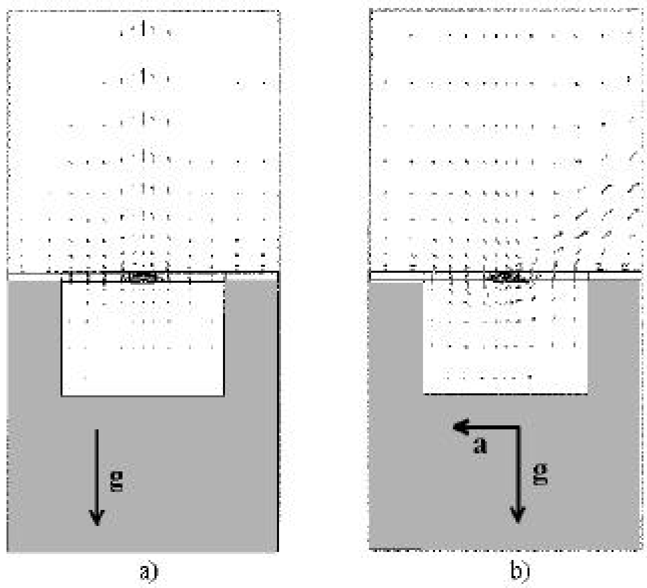

Figure 1. Convective flow from a suspended microheater from finite-element simulations.

where arrows from finite element simulation indicate convective airflow with gravity, and applied lateral acceleration in addition to gravity. When acceleration is applied, the change in the convective flow (which is now away from the resultant acceleration, Fig. 1b) causes a temperature difference between sides of the heated element. This temperature difference is proportional to the applied acceleration, and temperature sensors placed on either side of the heat source measure a differential output corresponding to the applied acceleration. The temperature sensing can be based on thermocouple or thermistor effect. We have implemented both types of devices for characterization, due to the inherent capability of CMOS layers for both types of measurements. Microphotographs of the fabricated thermopile device, and the thermistor device are shown in Figs. 2a and 2b, respectively.

In the thermopile device of Fig.2a, the meandering polysilicon heater encapsulated in glass passivation is seen in the center, suspended in air to obtain high thermal efficiency. The figure also shows two sets of closely spaced thermocouple junctions located on either side of the heater. Each of these hot junctions is in series with a cold junction located above the base silicon material. There are altogether 12 thermocouples connected in series in each side of the sensor to increase the output voltage signal. More recent designs include up to 50 such thermocouples in series. The final raw output voltage is taken as the difference of the outputs of the thermocouple sets on either side.

For the thermistor devices, the principle is the same, but a different configuration is utilized, as used in [7]. This is shown in the microphotograph of Fig. 2b. Two parallel suspended polysilicon resistors are fully-suspended with an adequate air-gap separating them. They are placed in a Wheatstone bridge circuit with reference to two parallel "cold" resistors which are not suspended, as shown in Fig. 2b. As a result of micromachining, the two parallel heaters

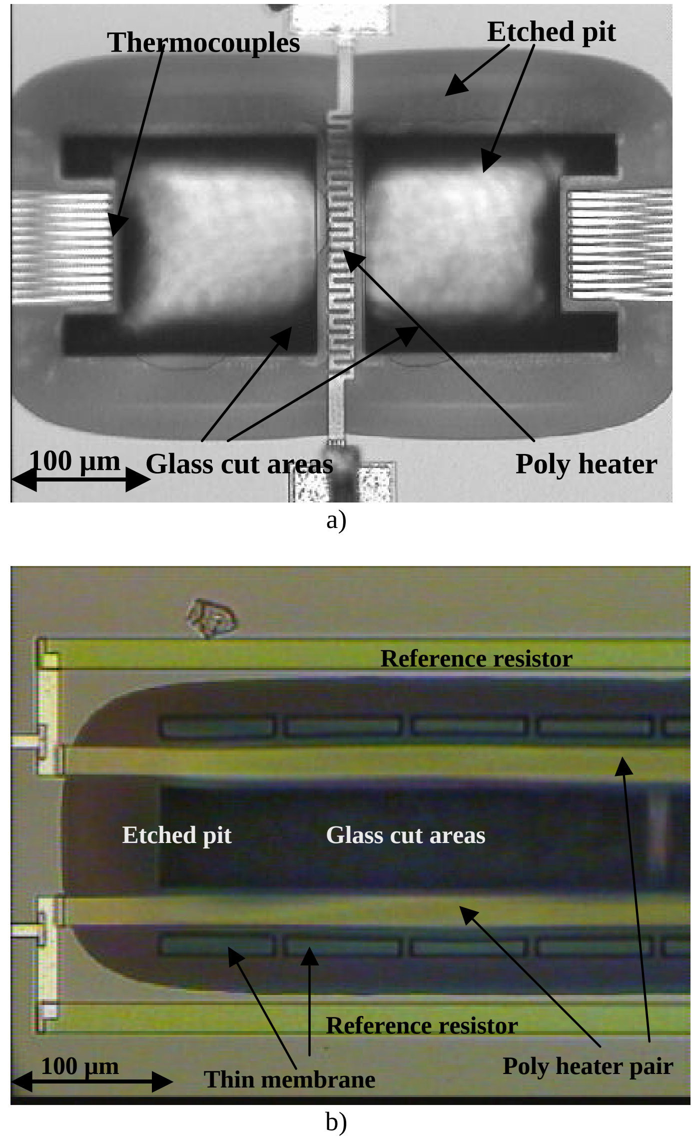

Figure 2. Microphotograph of the fabricated CMOS-compatible convective accelerometers, (a) thermopile type, and (b) thermistor type.

are both at the same high temperature until convective air-flow is made asymmetric by influence of acceleration along the sensitive axis.

III. SENSOR FABRICATION AND MEASUREMENT SETUP

Test chips were fabricated in a double-poly 2 μm CMOS *n*-well process through the MOSIS service, and were subsequently etched in our laboratory [4]. In Fig. 2a, the glass-cut areas are on both sides of the heater. In Fig. 2b, there is a large glass-cut area between the two parallel resistors, and thin glass regions on either side for better thermal isolation. The devices were silicon micromachined using a gaseous isotropic etchant, xenon-difluoride [10]. After approximately 6 min of etching [4] the structure is entirely suspended, up to the cold thermocouple junctions which must remain on the silicon substrate. The resulting devices are adequately thermally isolated from the substrate

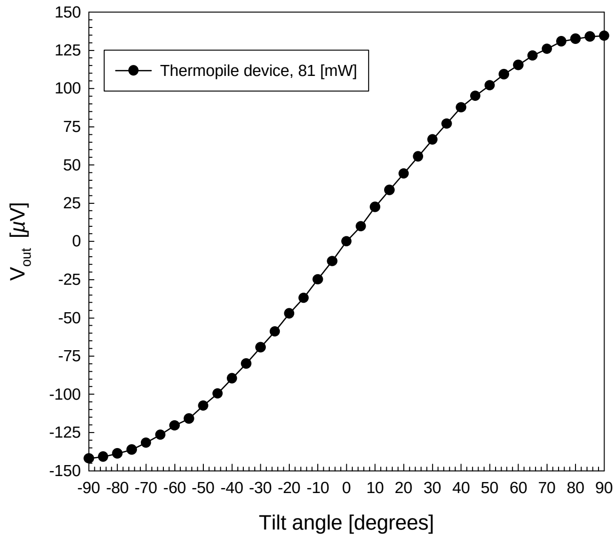

Figure 3. Measured performance of the thermopile device as a tilt-sensor at 81 mW input power -- tilt angle is angle between the earth ***g****-vector and the chip surface normal* ***n.***

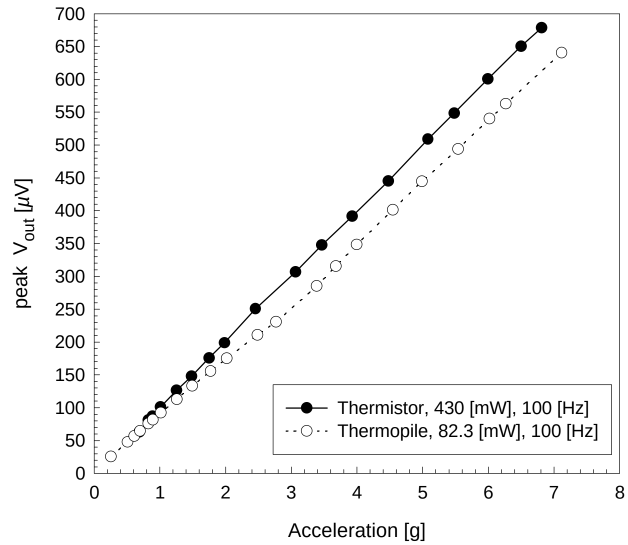

Figure 4. Measured performance of the devices as accelerometers from 0 to 7 g peak acceleration at 100 Hz.

to achieve temperatures as high as 1000 K for very small input powers (<100 mW for device in Fig. 2a). Better uniformity and etch-stop control could be obtained by employing the hybrid technique that we utilize in some other applications [4].

Measurements were performed under various applied conditions. Firstly, the sensor was mounted on an optical goniometer and tilted from $Q = -90$ to 90 degrees of angle, where Q is the angle between the chip's surface normal and the gravity vector. For this test, constant power was applied to the heater instead of constant voltage or current, to achieve a high bias stability of the suspended polysilicon resistor [9], such that approximately constant temperature was achieved. The recorded output voltage is shown in Figure 3. The measured voltage is a very good fit to the sine function as expected, since the equivalent acceleration projected on the sensitive axis of the device is proportional to $g \times \sin(Q)$.

The devices were subsequently measured on a vibration exciter (shaker), with acceleration range from 0 g to 7 g and vibration frequencies from 30 Hz to 3.0 kHz. Figures 4 and 5 show the measured outputs in terms of linearity and frequency response. Another important measurement is the sensitivity of the device while varying the input power to the microheater, i.e., varying the driving temperature. These measurements were also under conditions of applied acceleration on the shaker, and the results are given in Fig. 6 for both devices.

IV. DISCUSSION OF THE RESULTS

Tilt sensor results in Fig. 3a show a very good fit with the expected sinusoidal trend. Data could be plotted differently by computing the equivalent applied acceleration for each angle, as mentioned earlier. In that case, a linear result was obtained for acceleration vs. output voltage with<0.5 % linearity error and the slope of 136 μV/g.

Measurements of output voltage at applied acceleration, shown in Fig. 4 demonstrate very good linearity of both the thermopile and thermistor device in the range from 0 g to 7 g. The measured output voltage of Fig. 4 has a larger linearity error than in the measurements of Fig. 3, although still <2.6% over the 8 g applied acceleration range. It is expected that linear response would continue into >8 g range, although those tests could not be performed at this time. In comparison of the two devices, similar sensitivities are obtained at operation voltage of roughly 24 Volts, but in the case of the thermopile configuration, significantly lesser power dissipation is needed.

The thermopile devices also show very promising results for the frequency response in Fig. 5, which is fairly flat up to about 100 Hz, where the device's sensitivity decreases substantially. At the same time, the thermistor device has better frequency response characteristics, and respond up to 600 Hz. This is believed to be due to the significantly smaller spacing between sensing devices. Overall, the frequency characteristics are satisfactory, and demonstrate that this novel concept for inertial sensors gains much from the miniaturization technology such as CMOS MEMS.

Finally, the measurements in Fig. 6 demonstrate the dependence of sensitivity to the change in applied power to the heater. This result was expected, since the driving mechanism for the convection is the temperature difference between the microheater and the overall package. With linear increase in temperature, the sensitivity showed a proportional increase with a slope of 1.5 µV/g·mW and 0.67 µV/g·mW for the thermopile and thermistor device respectively. This is also an important results because it shows that for higher *g* applications, and with more sensitive output circuitry, power consumption could be significantly decreased for these devices.

The measurements presented here were performed on the devices packaged in ambient air. Since the sensors are

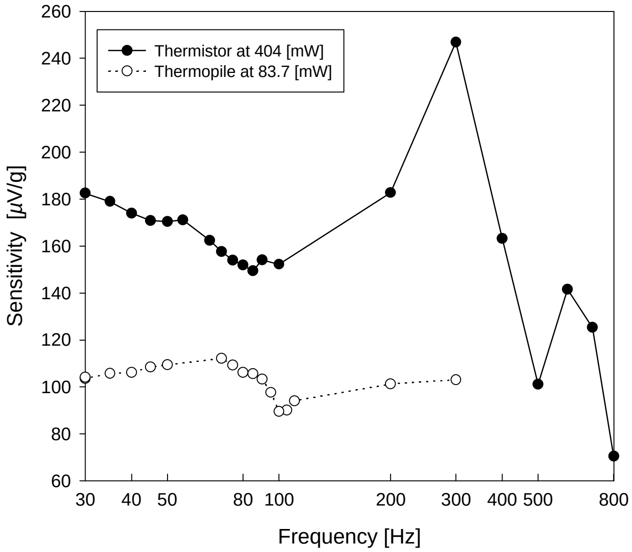

Figure 5. Measured sensors' frequency response (frequency vs. output rms voltage).

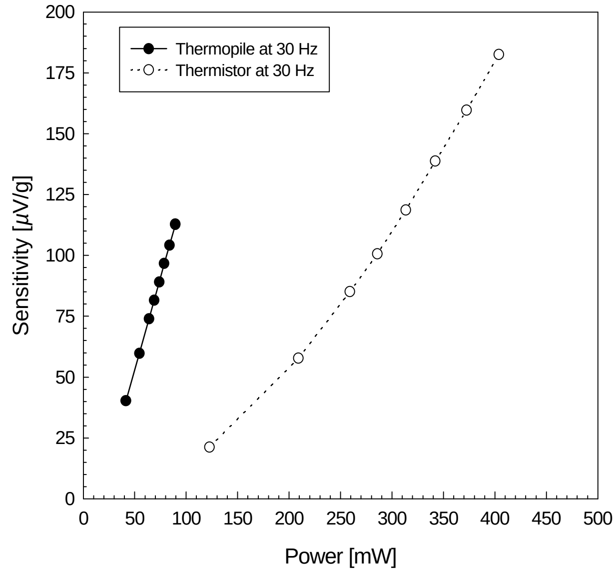

Figure 6. Measured sensors' power vs. sensitivity at 30 Hz.

convection-based, work is under way to characterize them in various gases, and under higher gas pressures, to achieve higher sensitivity [8]. It is expected that sensitivity at higher pressures could be traded off with higher frequency response at lower pressures.

V. Conclusions

We have reported on novel configurations of convective accelerometer and tilt sensor for numerous commercial and military applications. The sensors were fabricated in low cost CMOS technology with one additional maskless post-processing step. The devices showed good sensitivity and linearity characteristics, as well as a large range of operating frequency response. The CMOS implementation gives the advantages of low cost and easy integration with CMOS circuits. Much further work is needed to optimize the device and characterize performance using different gasses, pressures, and temperatures.

VI. Acknowledgement

The authors want to thank Ricardo Dao, John LaGrandeur, and Arkady Yampolsky of Humphrey, Inc. for the discussions of the concept of convective sensing. Also, authors wish to thank Chris Zincke for many technical discussions.

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